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Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology
National Institute of Standards and Technology
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EXPERIMENTS ESTABLISHING THE SIMILARITY OF WALL FIRE COMBUSTION

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ABSTRACT

A recent study[1] shows that fuel to air ratio of the flames, Ψ, controls the buoyant turbulent boundary layer combustion problem. The similarity of the fluid mechanics and the combustion at fixed Ψ, allows one to correlate and develop expressions for the flame thickness, δ_s, and flame radiance, N_r, in addition to correlating the temperature and velocity profiles. It also results in a soot volume fraction, f_v, and effective flame radiation temperature, T_f, independent of height and mass transfer rate for propylene flames.

INTRODUCTION

The overall objective is the development of models predicting the total heat transfer from the flames to the wall in both the pyrolysis and forward heat transfer zones of a spreading fire. The present study focuses on the pyrolysis zone supplying fuel to the fire. Figure 1 shows the burner used to study two-dimensional burning of a single wall. This is the simplest wall geometry for studying buoyant boundary layer mixing and combustion. A goal is to identify a fundamental similarity parameter that controls the buoyant turbulent combustion, but is insensitive to fuel chemistry. Having found such a parameter, one can then focus on the fuel type without being distracted by the fluid mechanics. Fuel is supplied uniformly through the individual water-cooled sintered-metal burners. Each burner measures 380 mm wide and 132 mm high; so that the overall height of the ten burners is 1320 mm. This is certainly large enough to achieve fully turbulent flames.

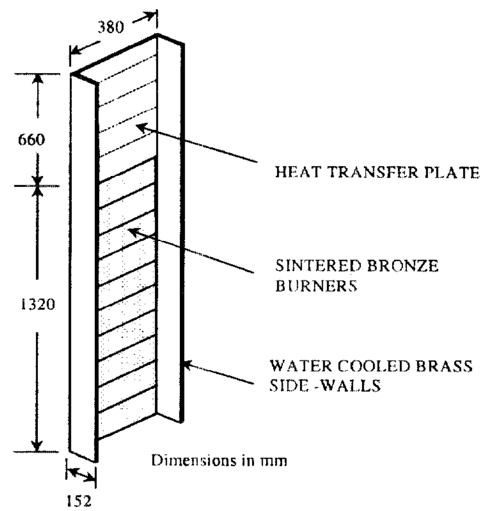

Figure 1 Gas Burner Apparatus

SOOT DEPTH

Our first task is to characterize the thickness of the luminous turbulent flames. The soot depth, δ_s, is measured by simply inserting arrays of 5 mm diameter glass rods into the flame perpendicular to the wall surface and rapidly withdrawing them after a two second exposure. Soot is deposited by action of thermophoresis. See Figure 2, below. The propylene (C_3H_6) flames were quite sooty. The rate of soot deposition (1) is driven by the temperature difference between the flame and glass rod, (2) is proportional to the soot volume fraction and (3) is independent of the soot particle size. Two arrays, each containing five rods, were inserted one at

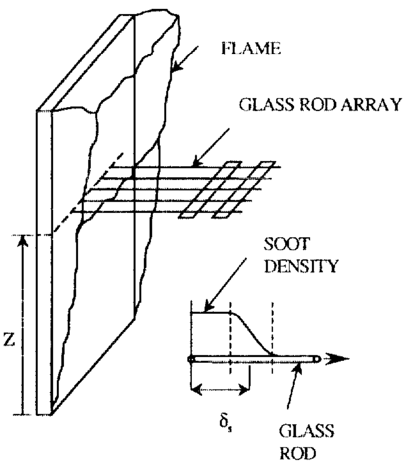

Figure 2 Sketch and detail of soot depth measurement

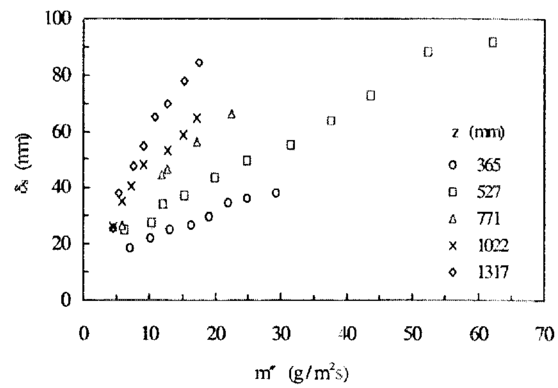

Figure 3 Measured soot depth, δ_s, vs. fuel mass transfer, $\dot{m}''$, at several heights, z

a time for each measurement at heights of 365, 527, 771, 1022 and 1317 mm. The lowest height of 365 mm insures readings well within the turbulent region. As shown in the figure detail, the soot deposition was uniform to the left of the first dotted line and then decreased gradually to zero over a distance about equal to the uniform deposition distance on the left. The soot depth, δ_s, is defined as the distance where the soot deposit is visually judged to have decreased to 50% of the maximum deposit on that rod. Figure 3 shows the variation of soot depth with mass transfer at different heights. Figure 4 shows the correlation of normalized soot depth by the fuel to air ratio of the flames, Ψ.

The fuel to air ratio, Ψ, is proportional to the total fuel supplied up to a given height divided by the accumulated entrainment of air up to the same height. As shown in Figure 10, below, the maximum mean upward velocity is insensitive to the fuel mass transfer and correlates according to

$$u_{\max} = 0.95\sqrt{2gz}\,.$$

According to Taylor's entrainment concept[2], the local air entrainment, $\dot{m}''_{air}$ into the flames is proportional to this upward velocity

$$\dot{m}''_{air} \propto \rho_A\sqrt{2gz}$$

where ρ_A is the density of ambient air.[1] The integral of the entrainment into the flame boundary layer up to height z is proportional to $\rho_A z\sqrt{2gz}$. This is to be

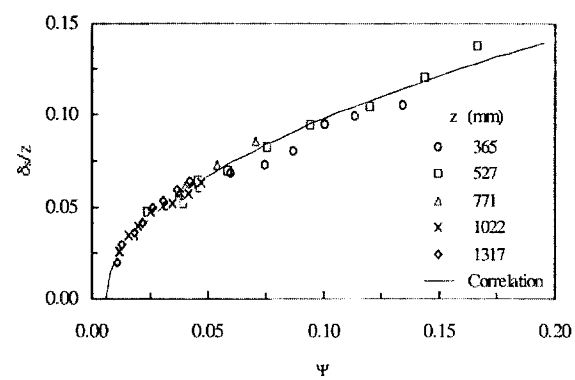

Figure 4 Correlation (solid line) of measured (symbols) normalized soot depth, δ_s/z vs. relative fuel richness, Ψ, at different heights, z.

[1] Strictly speaking, the entrainment is slightly dependent on the boundary layer width, which in turn depends on Ψ.

compared to the stoichiometric air requirement, s, of all the fuel supplied up to z; so that the relative richness is proportional to

$$\Psi \equiv \frac{s\int_0^z \dot{m}_F'' dz}{\rho_A z\sqrt{2gz}}$$

The correlation gives the empirical formula (solid line) for the flame thickness, δ_s,

$$\frac{\delta_s}{z} = 0.32(\Psi - \Psi_0)^{1/2} \quad \text{with} \quad \Psi_0 = 0.006.$$

This formula says that the soot depth disappears as $\Psi \rightarrow \Psi_0$. Indeed, the flames turn blue in this limit. The above formula applies to the turbulent region. One can use theoretical arguments to extend the soot depth formula to the laminar region, yielding

$$\frac{\delta_s}{z} = \left[1 + \left(\frac{z_t}{z}\right)^9\right]^{1/12} \left[0.32(\Psi - \Psi_0)^{1/2}\right] \qquad (1)$$

where $z_t = 110\,\text{mm}$ is a nominal laminar to turbulent transition height.

It is interesting to note that the condition $\Psi = \Psi_0$ also gives the overall turbulent flame height, z_f in meters, for a line fire against a wall

$$z_f = \left[\frac{s\dot{M}_f'}{\Psi_0 \rho_A \sqrt{2g}}\right]^{2/3} = \left[\frac{s\dot{Q}'}{\Psi_0 \Delta H_c \rho_A \sqrt{2g}}\right]^{2/3} = 0.047\left[\dot{Q}'\right]^{2/3}$$

for typical fuels releasing $\Delta H_c / s = 13.2$ kJ/g of O_2 consumed with heat release rates per unit width, $\dot{Q}'$ in kW/m, and the constant 0.047 in units of m(kW/m)$^{-2/3}$. This expression compares favorably with Ahmed's empirical correlation[3] $z_f = 0.052\left[\dot{Q}'\right]^{2/3}$ of visible flame heights against a wall.

TEMPERATURE

The temperature profile across the flame boundary layer was measured by a thermocouple rake. The measured temperatures were first time-averaged and then corrected for the radiant heat loss from the thermocouples as well as the radiant heat received from the flame. Our detailed knowledge of the radiation field produced by these propylene flames made it possible to accurately calculate these

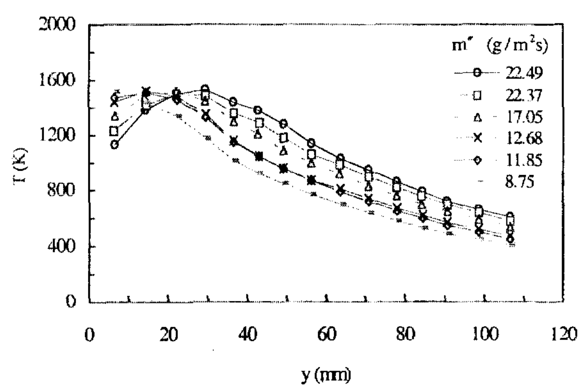

Figure 5 Corrected temperature, T, vs. distance, y, for various propylene mass transfer rates, $\dot{m}''$, at z = 771 mm from leading edge.

radiation corrections. It gives considerable confidence to these corrected temperatures. Figure 5 shows the corrected temperature profiles at a height of 771 mm for various mass transfer rates. Figure 6 shows the same temperatures plotted instead against y/δ_s. One sees that the temperatures are well-correlated inside the flame envelope. That is, the temperature profile inside the flame is independent of the fuel to air ratio, Ψ. In particular, the temperature at the flame boundary at $y = \delta_s$ remains around 1000 K for all values of relative richness, Ψ. The similarity correlation is not so good outside the flame. For leaner flames, having lower values of Ψ the temperature extends out to larger values of y/δ_s. It is shown later that this same lack of perfect similarity also occurs for the velcity profiles.

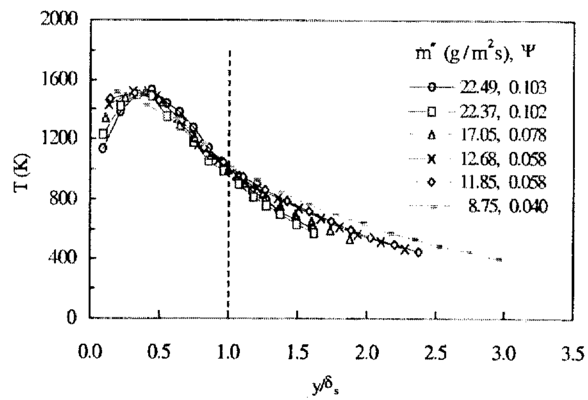

Figure 6 Corrected temperature, T vs. normalized distance, y/δ_s, for various propylene mass transfer rates, $\dot{m}''$, at z = 771 mm from the leading edge of the flame.

RADIANCE

Measurements of the local outward radiance* also support the similarity concept. Radiation comes only from the flames (i.e. the water-cooled sintered-metal burner emits negligible radiation.) Figure 7 shows the outward radiance from the flames vs. mass transfer at four different heights.

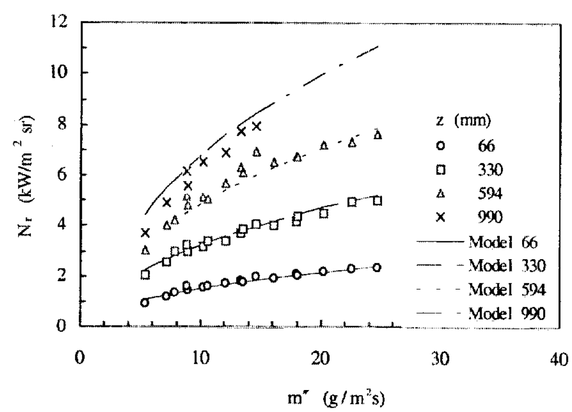

Figure 7 Measured and calculated flame radiance, N_r, vs. mass transfer, $\dot{m}''$, at four heights, z, for propylene.

The radiation comes almost entirely from soot in the case of propylene. More specifically, the radiance depends on the effective flame radiation temperature, T_f, the soot volume fraction, f_v, and the soot depth, δ_s. The effective flame radiation temperature is determined by first measuring the radiant emission from the flames at both 0.9 and 1.0 μm wavelengths. The emission is then compared to measurements of the absorption of externally imposed radiation at the same wavelengths. The inferred effective flame radiation temperature is 1375 K. The inferred temperature turned out to be independent of wavelength, heights and mass

* Here the outward radiance is defined as the radiant flux per unit solid angle in the outward normal direction.

transfer rate.[1] This invariance is, indeed, welcome. It simplifies the interpretation of data and development of models.

Making the usual assumption that the soot absorption coefficient of, $\alpha_\lambda = kf_v/\lambda$, varies inversely with wavelength, λ, it is shown[4] that the radiance, N_r, from a homogeneous cloud of soot having volume fraction f_v and depth, δ_s, is given by

$$N_r(T_f, f_v, \delta_s) = \frac{\sigma T_f^4}{\pi}\left[1 - \frac{15}{\pi^4}\psi^{(3)}\left(1 + \frac{kf_v\delta_s T_f}{C_2}\right)\right]$$

where σ is the Stefan-Boltzmann constant, C_2 is Plank's second constant, $k = 8.6$ is the soot extinction constant[5] and $\psi^{(3)}(1+x)$ is the Pentagamma function[4]. The expression, $\frac{15}{\pi^4}\psi^{(3)}(1+x)$, can be conveniently approximated[6] by $\exp(-3.6x)$, to yield

$$N_r(T_f, f_v, \delta_s) = \frac{\sigma T_f^4}{\pi}\left[1 - \exp\left(-\frac{3.6kf_v\delta_s T_f}{C_2}\right)\right] \tag{2}$$

Finally, upon rearranging Equation (2), $\frac{3.6kf_v\delta_s T_f}{zC_2} = -\frac{1}{z}\ln\left(1 - \frac{\pi N_r}{\sigma T_f^4}\right)$ and substituting for δ_s from Equation (1), one has

$$Y = \frac{-\ln\left(1 - \frac{\pi N_r}{\sigma T_f^4}\right)}{z\left[1 + \left(\frac{z_t}{z}\right)^9\right]^{1/12}} = \frac{3.6kf_v\left[0.32(\Psi - \Psi_0)^{1/2}\right]T_f}{C_2} \tag{3}$$

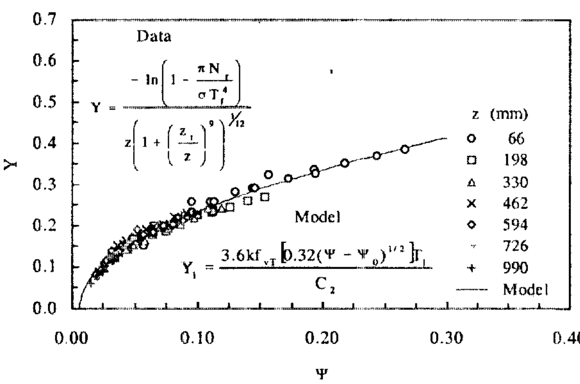

Figure 8 Correlation of measured radiance data, Y, for propylene flames at various heights, z, and mass transfer rates. Solid line is Equation (3).

The radiance data of Figure 7 is plotted in Figure 8 using the left-hand side of Equation (3) above, as ordinate and Ψ as abscissa. The correlation is excellent. It implies that the soot volume fraction f_v for these propylene flames is independent of height and mass transfer rates.

VELOCITY

Most, Sztal and Delichatsios[7] measured the velocity and temperature profiles of vertical turbulent ethane wall fires. The measurements were performed at Factory Mutual Research Corporation during the summer of 1982. The measurements were not correlated at the time. Now, with the present approach, both the velocity and temperature profiles are successfully correlated.

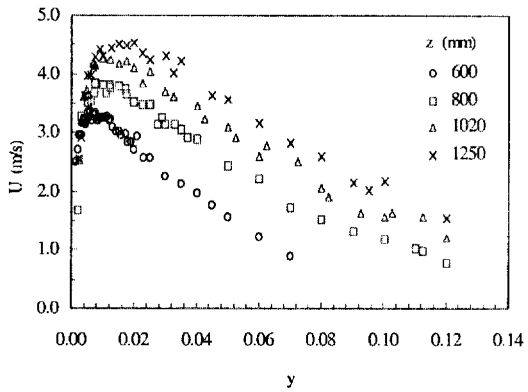

Figure 9 LDV measured velocity, U, vs. distance, y, for different heights, z, at mass transfer rate, $\dot{m}'' = 5.4\ \text{g/m}^2 s$

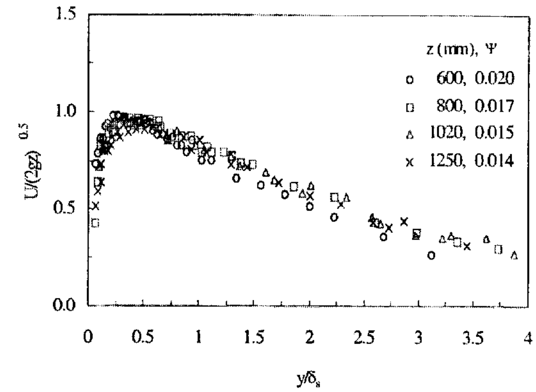

Figure 10 Correlation of $U/(2gz)^{1/2}$ vs. normalized distance, y/δ_s for different heights, z, at $\dot{m}'' = 5.4\ \text{g/m}^2 s$.

Their ethane flame temperature measurements are almost identical to those of Figures 5 and 6. Figure 9 shows their LDV velocity measurements, U, vs. distance, y, for different heights, z, for an ethane mass flow rate of $\dot{m}'' = 5.4$ g/m^{2}s. Figure 10 shows the same data correlated as $U/(2gz)^{1/2}$ vs. y/δ_s.

CONCLUSION

The similarity presented here has greatly simplified the development of flame heat transfer models for wall fires in the pyrolysis zone. Indeed reference [1] presents an algebraic model for the flame heat transfer in the pyrolysis zone for an arbitrary fuel having a given smoke point. The semi-empirical model is based on extensive measurements of methane, ethane, ethylene and propylene wall fires.

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